SURFACE-MOUNTED EDDY-CURRENT SENSORS FOR ON-LINE MONITORING OF FATIGUE TESTS AND FOR AIRCRAFT HEALTH MONITORING

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ABSTRACT

A new surface mountable eddy-current sensor, called the new Meandering Winding Magnetometer Array (MWM™-Array) has demonstrated the capability to monitor early stage fatigue damage, crack initiation and growth. This new capability is suitable for monitoring of on-line fatigue tests for coupons and complex components, as well as for monitoring of difficult-to-access locations on military and commercial aircraft. The sensor is thin and light weight. It can be surface mounted like a strain gage, but does not require an intimate mechanical bond, permitting use of compliant adhesives to improve durability.

The MWM is a "planar," conformable eddy current sensor that was designed to support quantitative and autonomous data interpretation methods. These methods, called grid measurement methods, permit crack detection on curved surfaces without the use of crack standards, and provide quantitative images of absolute electrical properties (conductivity and permeability) and coating thickness without requiring field reference standards (i.e., calibration is performed in "air").

Components of this ongoing work on fatigue monitoring and applications for specific aircraft are being funded by the Naval Air Warfare Center, Aircraft Division, Patuxent River, the FAA, the Air Force, and internally by JENTEK Sensors, Inc. Application of the MWM-Array technology to detection and characterization of the onset of widespread fatigue damage for commercial and military aircraft was described in a paper presented last year at the First Joint DoD/FAA/NASA Conference on Aging Aircraft. This paper presents new results for on-line crack initiation and growth monitoring.

1. INTRODUCTION

The decision to fly and support military and commercial aircraft well beyond their original design lives requires an increased focus on escalating costs associated with inspection, maintenance and repair. In many cases, the Air Force is electing to extend the life of current inventory aircraft for an additional 25 years or more (e.g., T-38, F-16, C-130E/H, A-10, AC/RC/KC-135, U-2, E-3, B-1B, B-52H). [1,2] More rapid and cost effective inspection capabilities will be necessary to safely support these life extensions.

Several nondestructive testing needs for eddy current sensing are derived from this new cost and life extension focus for structures (engine issues not included here, see reference 13):

1. **Rapid mapping** of fatigue damage over wide areas.
2. **Reduced calibration** requirements and reduced requirements for field standards.
3. **Difficult-to-access** location monitoring without disassembly.
4. ***Continuous on-line crack initiation and growth monitoring***
5. **Rapid hidden corrosion mapping** over wide areas
6. **Second layer crack detection**
7. **Earlier crack detection under fastener heads** with fewer false alarms.

Each of these areas can be addressed by the MWM and grid measurement methods. The first two areas have been the focus of several customer and government funded efforts and are now being transitioned to field use. The third and forth needs are addressed in this paper and are the focus of ongoing funded efforts. Deep penetration arrays are not addressed in this paper, but are currently the focus of several ongoing efforts by the authors and MWM based solutions to needs five and six will be the focus of future papers. The last topic is not currently being addressed because of the substantial focus on this need by other researchers.

First a review of the MWM and grid measurement methods is provided along with a review of capability for fatigue monitoring using scanning systems. Then preliminary results of on-line fatigue monitoring with MWM-Arrays are presented.

2. MWM WITH GRID MEASUREMENT METHODS

Figure 1 shows a photograph of the MWM probe with conformable sensor tip and Figure 2 shows an MWM probe inspecting a curved turbine blade surface.

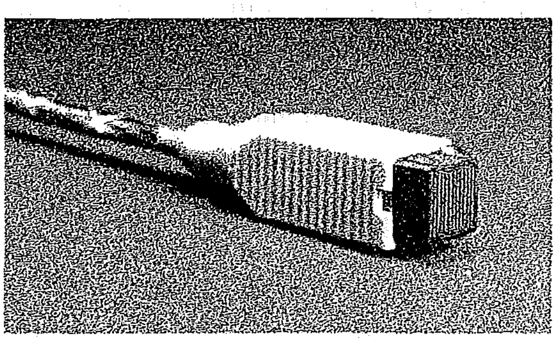


Figure 1: MWM probe with a conformable foam "probe tip" for inspecting flat, convex, concave and tapered surfaces.

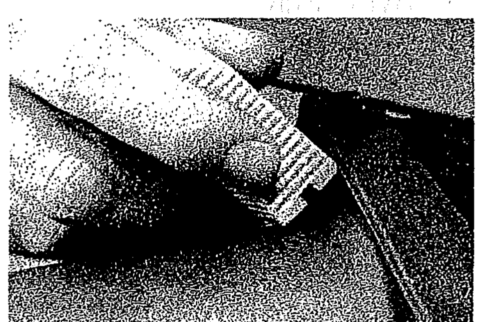


Figure 2: MWM Probe inspecting complex curve on turbine blade surface.

The patented measurement grid methods for calibration and property estimation offer the unique capability *to measure absolute electrical conductivity without the use of calibration standards*. Calibration is accomplished simply by holding the MWM probe in air, away from any conducting objects. The potential to measure within less than ±1% IACS (International Annealed Copper Standard = 5.8E7 S/m) absolute accuracy, without using reference standards, for conductivity ranging from 0.5% to 60% IACS (i.e. for most metal alloys) has been demonstrated using the MWM on conductivity standards provided by Boeing and ALCOA. This includes all non-magnetizable structural and engine alloys. Also, the capability to measure metallic coating thickness has been demonstrated without using thickness standards, with a new multiple frequency grid measurement algorithm (patent pending). Furthermore, the capability to detect cracks on curved surfaces for magnetizable material such as steel has been demonstrated with only a "calibration in air." For example, paint coating thickness can be measured on steel, **without thickness standards**.[2-12]

A schematic of the original MWM winding designs is shown in Figure 3. ***Instead of designing the windings first and then trying to model them, the MWM was designed to match the Cartesian coordinate (x,y,z) model formulation*** for the magnetic diffusion equation. Later generation designs have further improved the agreement between the actual sensor response and the model predictions.

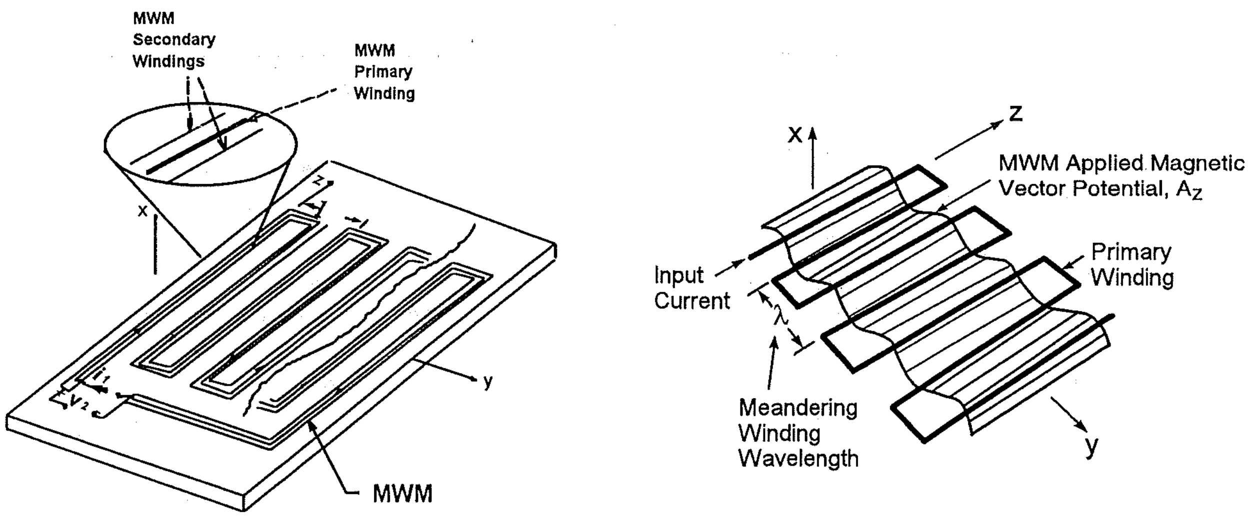


Figure 3: The MWM sensor and the "standing wave" magnetic vector potential, A_z, produced by the dominant Fourier mode.

This accurate sensor response prediction permits model-based simulations to be performed for sensor optimization and provides real time property measurements with minimal calibration requirements. This is also what makes absolute conductivity and coating thickness measurements possible without using reference parts for calibration.

The MWM has a primary winding fabricated in a square wave pattern, as shown in Figure 3. The MWM winding spatial wavelength is indicated by λ. A current, i_1, is applied to the primary winding and a voltage is measured at the terminals of the secondary windings. Two secondary windings meander on opposite sides of the primary to maintain symmetry. The magnetic vector potential produced by the current in the primary can be accurately modeled as a Fourier series summation of spatial sinusoids, with the dominant mode having the spatial wavelength λ.

The Grid Measurement Methods

Measurement grids are generated off-line and stored in a "grid library" for various coating systems or uncoated media and for different MWM sensor geometries and operating frequencies. This is accomplished using a continuum electromagnetic model of the MWM interactions with multiple layered materials, such as aircraft skins with Alclad coatings or metallic oxidation protection coatings on turbine blade super alloy substrates. The patented grid methods are then used to provide real-time quantitative estimates of the material properties of interest.

A single measurement grid at a single MWM operating frequency is designed to convert the impedance magnitude and phase measurement to a measure of up to two unknowns. As illustrated in Figure 4, the problem with conventional eddy-current methods is that empirical correlation tables that relate the amplitude and phase of a lift-off compensated signal to properties of interest such as crack size or hardness will be inherently limited. With conventional methods, only signal amplitudes are typically provided, not absolute conductivities. By providing absolute conductivities, the MWM and grid measurement methods permit the application engineer to tap into decades of scientific research that relates electrical properties to "dependent" properties such as hardness and residual stress. Also, the elimination of calibration standards to correct for unmodeled instrument and sensor behavior, results in a substantially wider range of reliable and repeatable measurement performance. For example, the same MWM probe, shown in Figure1, after a "calibration in air" can be used to make absolute conductivity measurements over a frequency range from 40 kHz to 15 MHz on Aluminum, without recalibration, and can then be used for paint thickness measurement on steel, again without recalibrating.

Figure 5a shows a conductivity/lift-off grid and Figure 5b shows a coating thickness/lift-off grid. (note lift-off is the relative proximity of the MWM winding plane to the first conducting layer of the material under test). These particular grids include the conductivity ranges relevant for the superalloys U520 and In718 and for MCrAlY or PtAl coatings typically used in turbine blades. Many other measurement grids have been constructed for other pairs of unknowns (e.g. magnetic permeability and lift-off for low alloy steel). The JENTEK GridStation software converts the MWM impedance measurements, using a look-up table (represented by the measurement grid) and interpolation algorithm, into estimates of lift-off and conductivity or two other unknowns of interest. Also, multiple grids can be used to solve problems with more than two unknowns (e.g., four unknowns: coating thickness, coating conductivity, substrate conductivity, and lift-off for turbine blade coating systems of for an Alclad coated aircraft skin).

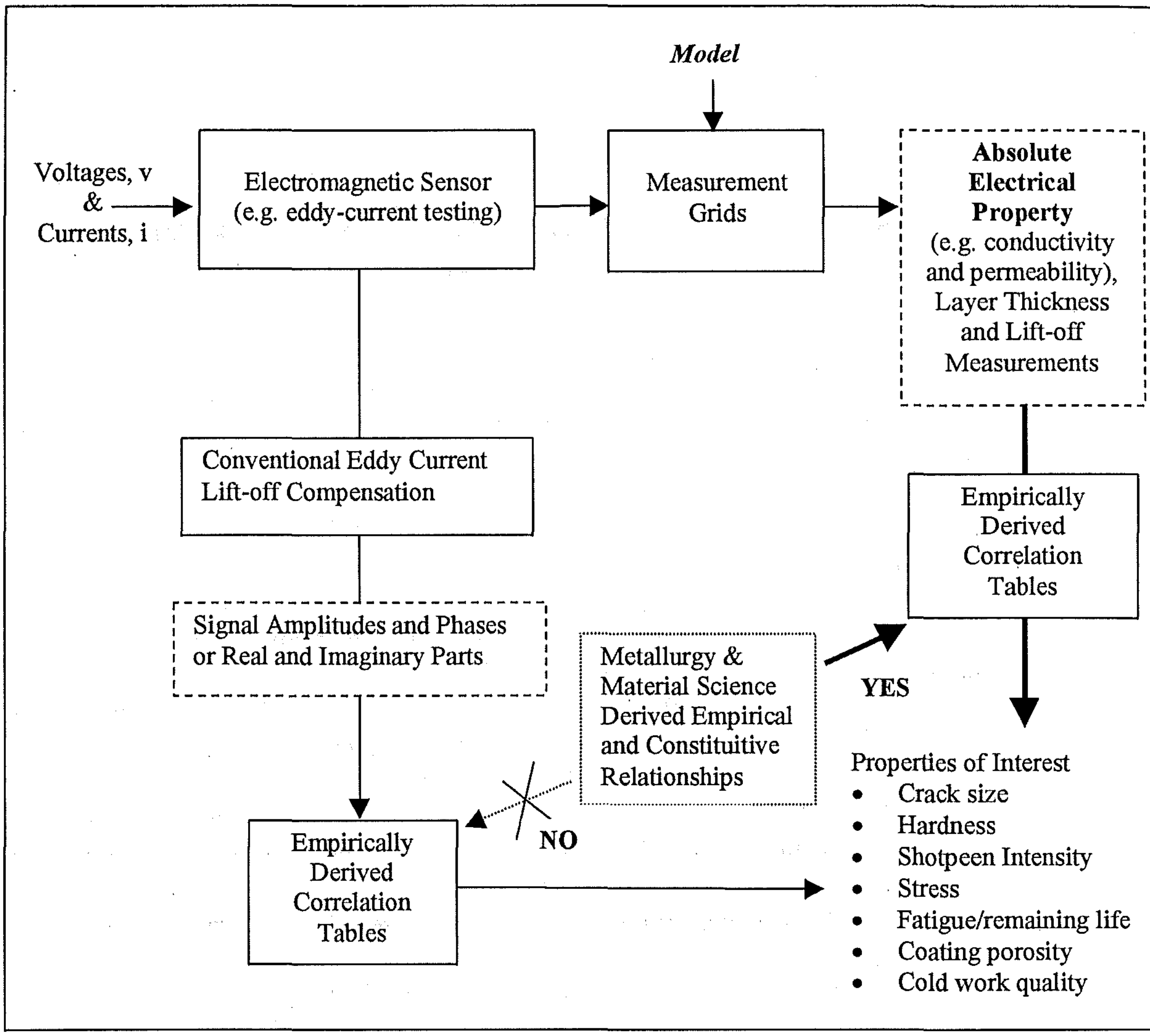
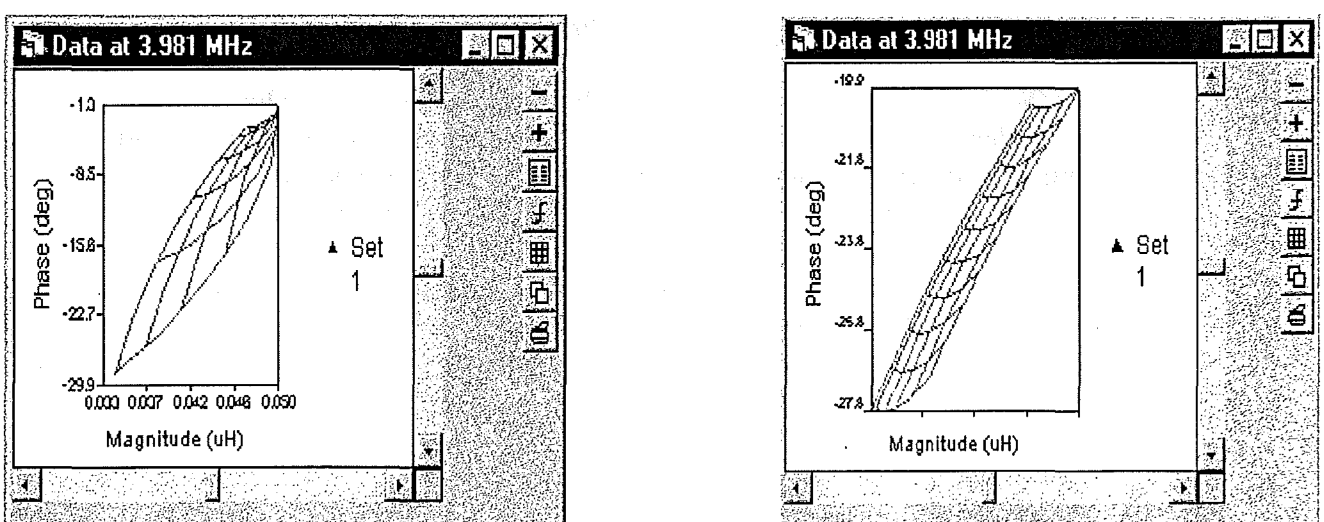


Figure 4: Schematic diagram describing the use of the model based grid methods, as compared to more conventional eddy-current lift-off compensation methods.



(a) (b)

Figure 5: (a) Uniform substrate conductivity/Lift-off grid, (b) Coating thickness/Lift-off grid, printed from JENTEK GridStation Software.

8. APPLICATION OF SURFACE SCANNING MWMs TO FATIGUE MAPPING

Fatigue studies with the MWM began over five years ago. The initial focus was on surface scanning applications and on demonstration of the capability to inspect wide areas. For example an MWM scanning system is installed at ALCOA which provides rapid scanning of steel roll surfaces without contact. This system uses the lift-off (proximity) measurement provided by the MWM to control its own position relative to the roll surface and provide C-Scan (2 dimensional) images of conductivity, used to detect cracks at up to 2 ft./second. This same capability is being designed into rapid scanning tools for wide area aircraft structure inspections, without paint removal.

During the last four years, investigations into the mapping of early stage fatigue damage and fatigue cracks using the MWM and grid methods have included:

1) Correlation of MWM measurements with loading history, optical microscopy, and x-ray diffraction for aluminum alloy bending fatigue coupons
2) MWM measurements on full-scale bulkhead fatigue test specimen
3) MWM measurements on the passenger window lap joints and the skin panels under the pilot window post of a service-exposed Boeing 737 at the FAA/AANC (discussed later in this paper).
4) MWM measurements on other fatigue tested and service exposed commercial and military aircraft components.
5) On-line fatigue monitoring using MWM-Arrays (discussed later in this paper).

Bending Coupon Study of Early Stage Fatigue Detection

MWM conductivity/lift-off grids for both stainless steel and aluminum alloys were used to demonstrate the correlation of MWM conductivity measurements with cumulative fatigue damage. Hourglass and "dog-bone" shaped specimens were exposed to varying fractions of their fatigue life at a known alternating stress level. MWM electrical conductivity measurements for some of the dog-bone specimens are shown in Figure 3, as a function of fatigue life. As illustrated in the figure, significant changes in conductivity were observed. Figure 4 provides MWM scans for coupons exposed to fully reversed bending. For Al 2024, the MWM begins to detect significant reductions in conductivity at about 60% of fatigue life.

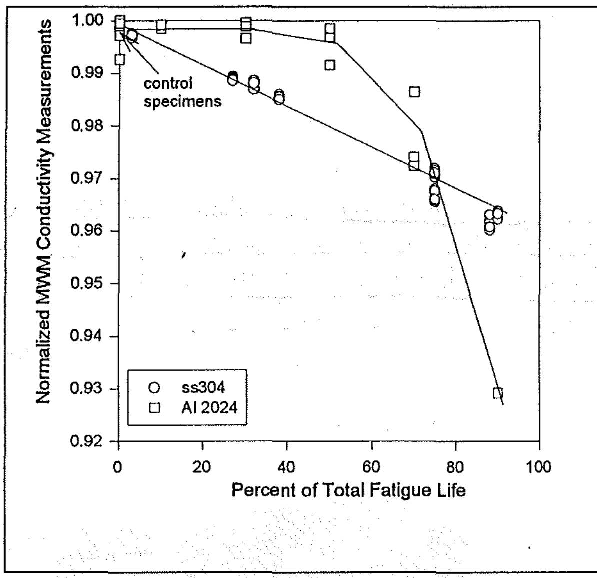


Figure 3: MWM conductivity measurements as a function of percent fatigue life: (a) 304 stainless steel (b) 2024 aluminum.

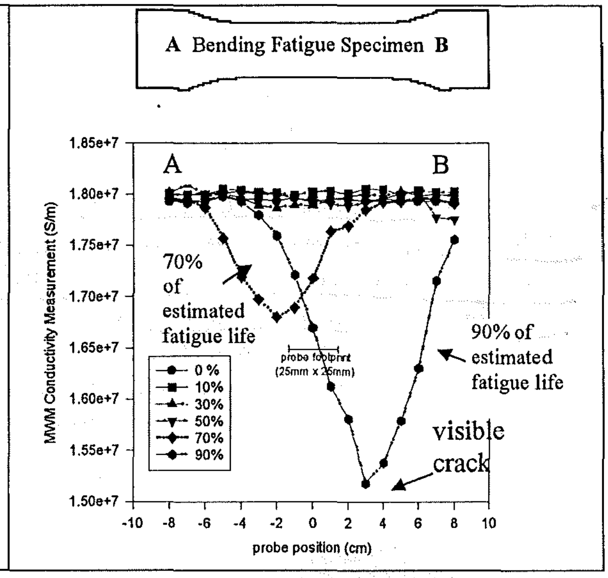


Figure 4: Plots of MWM absolute conductivity scans across 2024 aluminum hour-glass specimens fatigued to 0, 10, 30, 50, 70 and 90 percent of fatigue life.

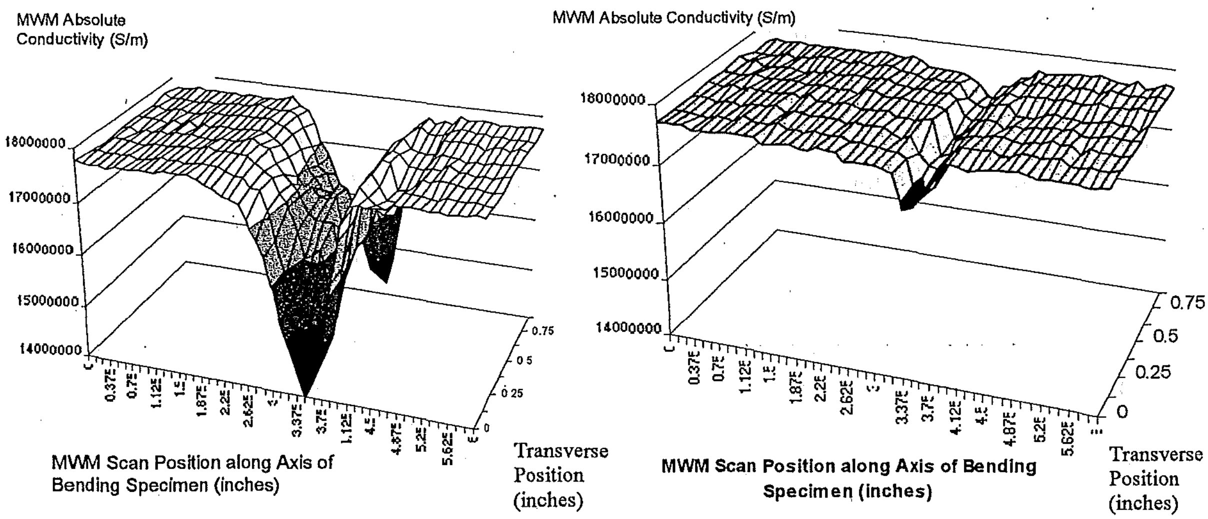
To evaluate the ability of the MWM to detect the spatial distribution of fatigue damage, the sensor was scanned along the length of the specimens. These measurements reveal a pattern of fatigue damage focused near the dogbone specimen transition region for both the 70 and the 90 percent specimens (see Figure 4). The minimum conductivity at the 3 cm point on the specimen that reached 90 percent of its fatigue life corresponds precisely with the location of a visible crack. This data was taken several years ago. New instrumentation and software now permit rapid scanning of these specimens at speeds over 3 inches per second for aluminum fatigue monitoring. Speed limits depend on the flaw detection requirements (e.g. minimum flaw size detection required). This rapid scanning capability should provide substantial cost savings for wide area inspection. Scanning arrays are also under development with wide scan paths of 3 inches or more.

Figure 5 provide C-scan images of the 90 percent specimen with the MWM in two different orientations. (note the MWM footprint for the data in Figures 3 and 4 was 1 inch by 1 inch; the MWM footprint for the data in Figure 5 was 0.5 inch by 0.5 inches. The presence of a damaged region in the vicinity of the crack is indicated by the depressed conductivity on either side of the crack, even when the crack is not under the footprint of the sensor. In other words, bending fatigue in aluminum produces an area damaged by microcracks prior to the formation of a dominant macrocrack, and that damaged area is detectable as a significant reduction in the MWM measured conductivity.

Photomicrographs have shown that clusters of microcracks, 0.001 to 0.003 inches deep, begin to form at this stage. Although detectable with the MWM, these microcrack clusters were not detectable with liquid penetrant testing, except at the very edge of the 90% specimen. This same behavior has been observed for MWM measurements on military and commercial aircraft structural members.

When the longer MWM winding segments are oriented perpendicular to the cracks, the MWM has maximum sensitivity to the macrocrack and the microcrack clusters. When the MWM is oriented parallel to the crack, the MWM has minimum sensitivity to the macrocrack and microcrack clusters (see Figures 5a and 5b). The directional dependence of the sensor response in the fatigue damaged area adjacent to the macrocrack indicates that the microcracks that form at early stages of fatigue damage are highly directional and, in this case, are aligned with the bending moment axis. Similar measurements on complex aircraft structural members have shown similar behavior at early stages of fatigue damage, before detectable macrocracks have formed.

Note that the microcrack density and size increases are indicated by a larger reduction in the MWM absolute conductivity measurements. Thus, as expected, the microcrack size and density increase near the coupon edges and are lower at the center.



(a) (b)

Figure 5: Two-dimensional MWM Absolute Conductivity (S/m) scans with windings (a) perpendicular to macrocrack orientation (i.e. perpendicular to bending moment axis) and (b) parallel to macrocrack orientation for cracking in the aluminum bending coupon shown in Figure 5.

Early Stage Fatigue Measurement: Boeing 737 Study (data presented originally at 1997 Air Transportation Assn. NDT Forum)

MWM measurements were made at the FAA/AANC on the lap joint of the Boeing 737 (test bed at Sandia National Laboratories) near the passenger windows and on the skin panels under the pilot window post. The Alclad layer thickness on the 0.040 inch (1.02mm) thick Boeing 737 fuselage skin was approximately 0.002 inches (.051 mm). The skin depth at the highest frequency was selected to be slightly greater than the Alclad thickness, while the skin depth at the lowest frequency was selected to be less than 25% of the total 0.040 inch (1.02 mm) outer skin thickness.

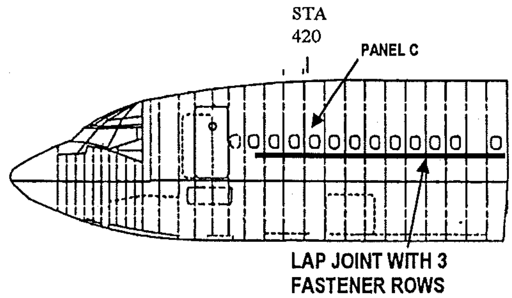
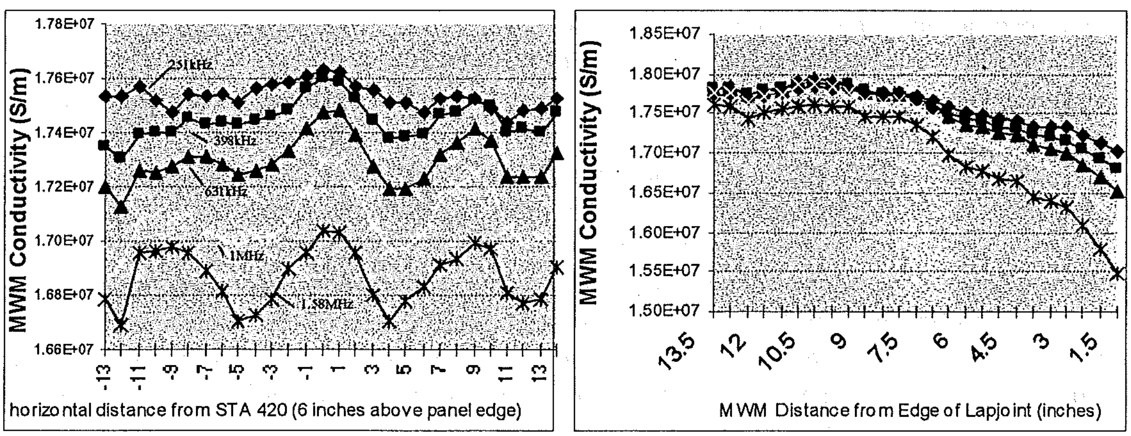


Figure 6: Locations of 737 panels tested during visits to the FAA/AANC.

Panel C (shown in Figure 6), containing the passenger windows above the lap joint near the center of the aircraft, exhibited substantial MWM measured conductivity variations. MWM horizontal and vertical scans identified regions near and <u>away</u> from fasteners that exhibited fatigue-like features associated with microcracking and thus represented the most likely locations in the lap joint for macrocrack formation. MWM fatigue coupon studies on 2024 aluminum alloy, described earlier, demonstrated detection of microcrack clusters after 50% of fatigue life. Figure 7 shows a horizontal scan <u>several inches above</u> the top fastener row. For this scan, the MWM measured conductivity has minimums that correspond consistently with the vertical window edge locations. Thus, several inches above the lap joint fastener rows, substantial bending fatigue-like damage was detected by the MWM. The bending fatigue coupon data suggests that this region is



(a) (b)

Figure 7: MWM multiple frequency scans on Boeing 737 at FAA/AANC (a) horizontal and (b) vertical scan data on panel C. Lower conductivity, measured at higher frequency, indicates that greater damage is present nearer to the surface of the tested material.

beyond 60% of its fatigue life, although it probably does not contain macrocracks, which would be detectable with conventional differential eddy-current methods. Vertical scans showed that this damage begins near the bottom of the windows and increases steadily, with the maximum damage occurring at the fasteners, as expected. The vertical scan data is shown in Figure 7b. <u>The key is that this damage is detectable more than six inches</u>

away from the fasteners. Thus, when scanning a lap joint it may be desirable also to scan the regions above and below the lap joint.

For this particular 737 aircraft, five cracks have been documented on the lap joints immediately above and below the passenger windows on the port side of the aircraft. Each of these cracks occurred within one fastener of the edge of the window. Two of these cracks, at the fasteners, have not been repaired and are detectable with conventional eddy-current methods. Three of the cracks had been repaired by addition of patches at these locations. This provides a partial validation of the MWM capability to detect WFD onset.

One additional observation based-on the MWM data is that the edges of a patch should be away from the minimums in the MWM conductivity (e.g., a location of maximum fatigue damage). Additional scans on other commercial aircraft components have shown similar promising results. Information such as this can improve selection of patch location and size, potentially reducing follow-on maintenance costs. Ultimately, the MWM information might be used to identify specific regions that require fastener inspections, as well as to support inspection, maintenance scheduling and redesign efforts. Furthermore, as aircraft are pushed well beyond design life, the requirement for wide area fatigue mapping for100% of skin panels may be necessary.

9. SURFACE MOUNTED MWM-ARRAYS FOR CRACK INITIATION AND GROWTH MONITORING

This work is currently under funding from the Navy for crack initiation evaluations and investigation of applications on Navy Aircraft, and from the Air Force for investigation of on-line monitoring capability for the outboard engine truss mount tang for the C-130 aircraft. Preliminary results of work at JENTEK Sensors are presented here.

Figure 8 provides a photograph of the first prototype MWM-Array mounted in a 0.25 inch hole in a 2024 aluminum fatigue test coupon. The MWM-Array used in this first test had eight sensing elements approximately 1 mm in width with 1mm separation between centers. First, several specimens where run to failure to determine the response from crack initiation to failure. Figure 9 shows a photograph of the same sensor after failure. Then several specimens were stopped at various stages of crack initiation and propagation. Figure 10 shows several of the tested specimens. Ongoing work will include metallographic examination of some specimens.

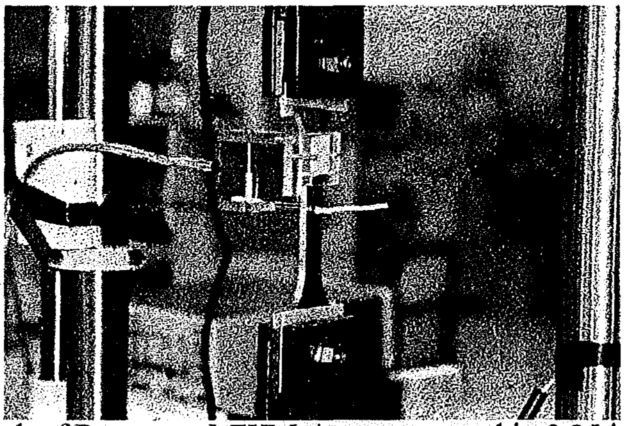


Figure 8: Photograph of Prototype MWM-Array mounted in 0.25 inch hole on fatigue test coupon.

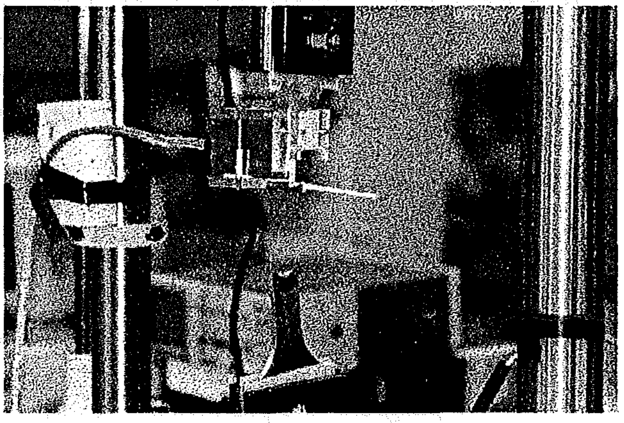


Figure 9: Photograph of specimen with MWM-Array after failure.

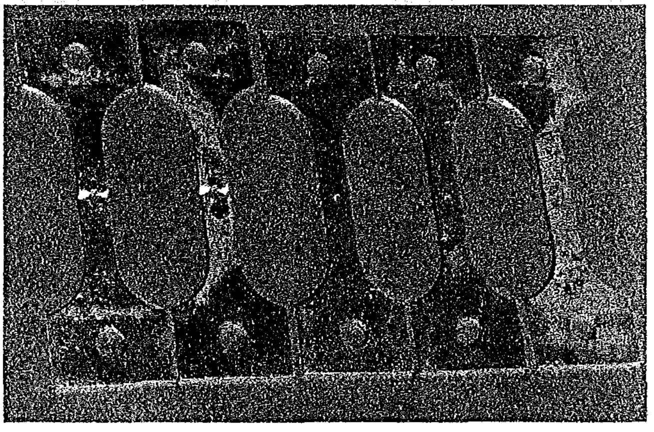


Figure 10: Photograph of five specimens monitored with the MWM-Array.

Figure 11 provides the results of a specimen test using a one dimensional MWM-Array with eight individual sensing elements spaced 1 mm apart. For the test coupon, six of these elements where in contact with the aluminum surface inside the drilled 0.25 inch hole (the third element channel failed, so data for the third element is not provided). This same data is plotted in a different format in Figure 12.

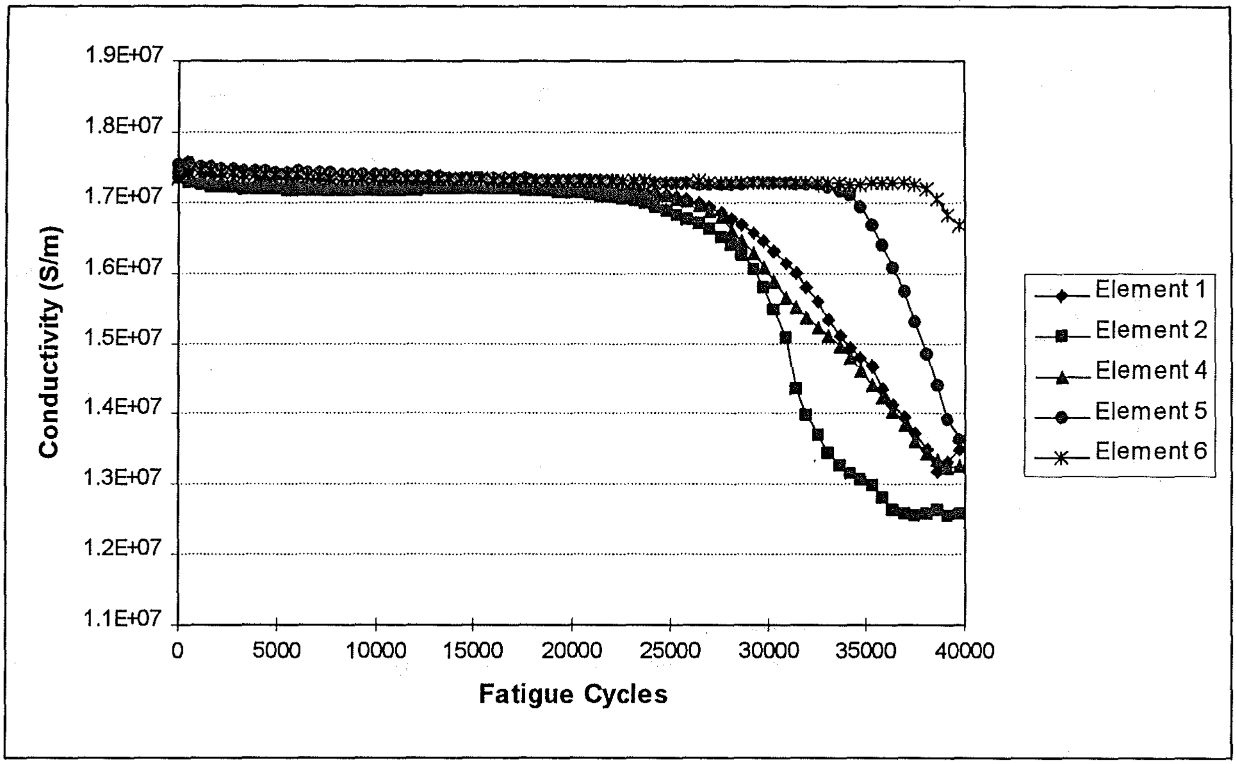
Figures 11a and 12 a provide the absolute conductivity measurements at each element of the MWM-Array. In figure 11a these are provided as a function of fatigue cycles for each element. In Figure 12a the data is provided as a function of element position along the axis of the drilled 0.25 inch hole. The MWM-Array was located using a modified version of the fixture shown in Figure 8.

This data indicates crack initiation at around 25,000 cycles. The crack appears to initiate near element 2, immediately propagates to the edge at element 1 and then gradually propagates to the other edge and is detected by element 6. This particular test was stopped when element 6 began to detect the crack. Upon examination at 100 times magnification, no crack was apparent on the outer surface near element 6.

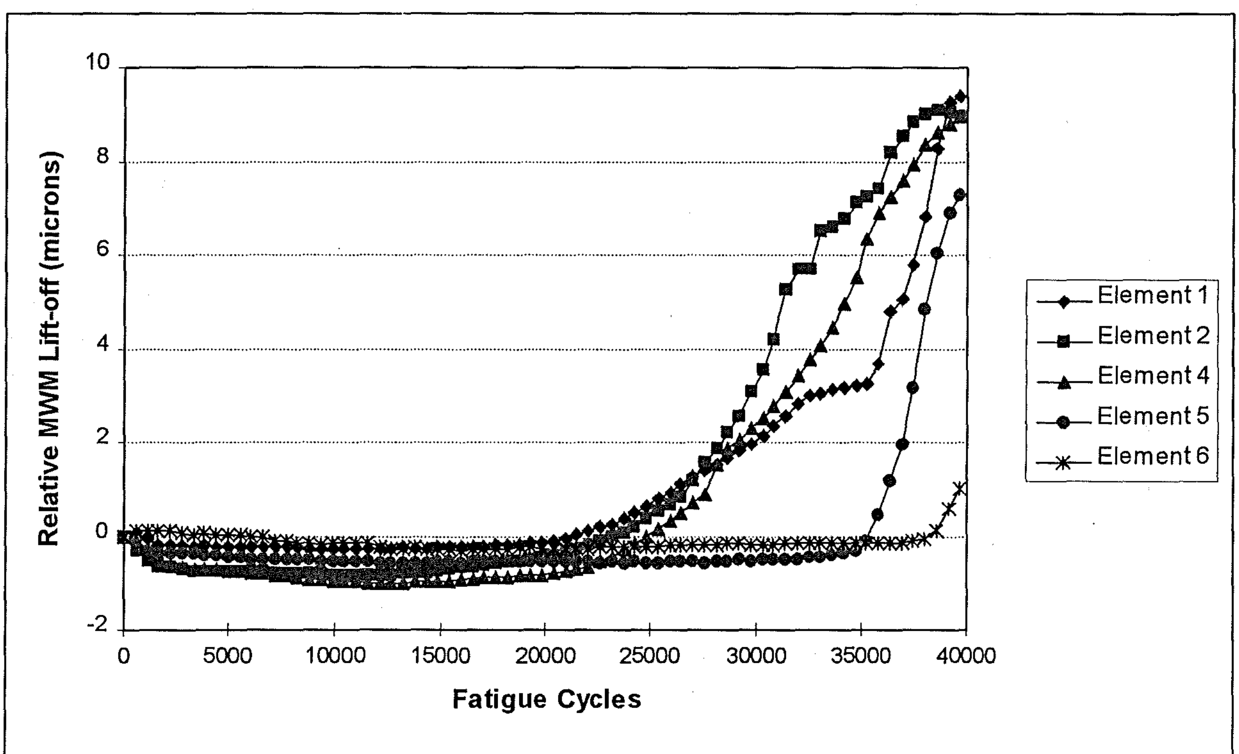
In other tests, specimens have been stopped with no visible crack indications after the MWM has detected damage. Continuing efforts will include metallographic examination of specimens to determine the earliest stage of crack initiation detectable by the MWM-Array for aluminum.

The lift-off data provided in Figures 11b and 12b, illustrate (1) the "settling" of the MWM during initial testing, as the sensor adjusts to the surface, and (2) the effect of the opening of the crack during later stage testing, which increases the effective lift-off. Monitoring of "effective lift-off" signals using the MWM-Array for deep cracks (over 0.1 inches) may provide the capability required for "compliance" monitoring of large cracks to estimate depth on-line.

Although this is a work in progress, the preliminary results demonstrate the feasibility of continuously monitoring crack initiation and growth during load cycling with the MWM-Array. This new capability is suitable for use in difficult-to-access locations on military aircraft, such as at the outboard engine truss mount tang of the C-130, or the tail attach bulkhead of the F-16.

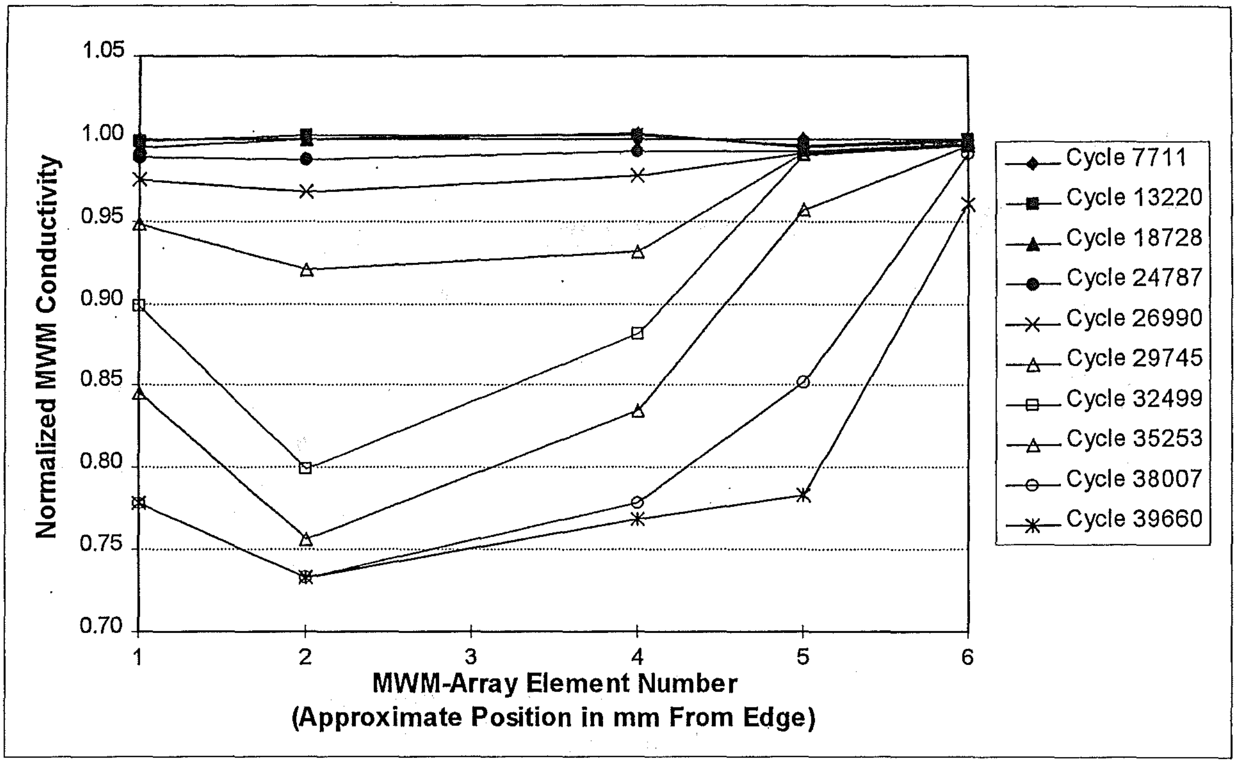


(a)



(b)

Figures 11a and 11b: Conductivity and lift-off changes during fatigue cycling of Al 2024 T3 measured by five elements of the MWM-Array sensor, spaced at 1 mm intervals through the thickness. R = -1; $\sigma_{nom\text{-}max} = 33$ ksi. The central hole represents an elastic stress concentration factor of 2.422.



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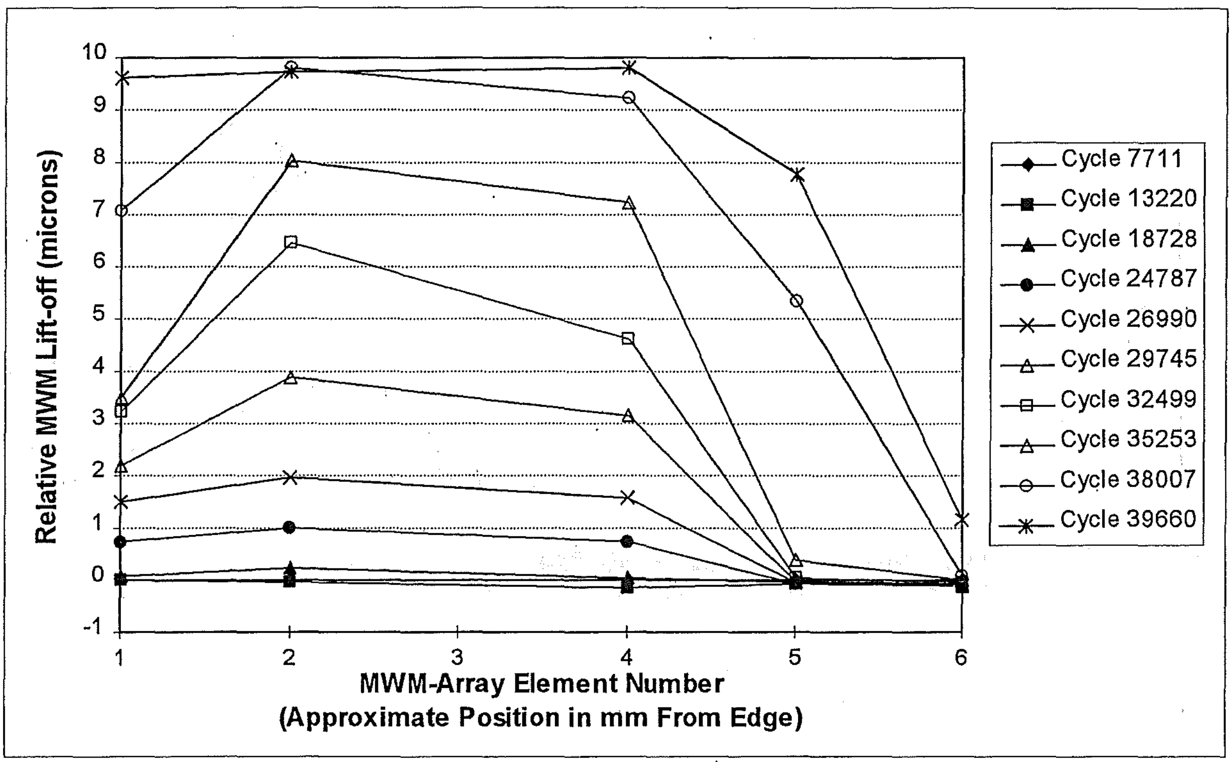

(b)

Figures 12a and 12b. Conductivity and lift-off changes during fatigue cycling of Al 2024 T3 measured by five elements of the MWM-Array sensor, spaced at 1 mm intervals through the thickness. R = -1; $\sigma_{nom\text{-}max}$ = 33 ksi. The central hole represents an elastic stress concentration factor of 2.422.

5. CONCLUSIONS

The capability of the MWM-Array to monitor crack initiation has been demonstrated. Continuing efforts will establish the stage of initiation detectable with the MWM for aluminum. Funded efforts include application to problems on military aircraft as well as online monitoring of fatigue tests. The capability to monitor fatigue tests continuously at critical locations should permit identification of "fatigue" parameters, such as local "effective" conductivity that may provide a basis for improved residual life prediction by providing real time measures of actual material fatigue state. This is not only valuable for fatigue test monitoring but might be usable in damage tolerance methods to provide improved inspection scheduling. Also, monitoring of "effective lift-off" signals using the MWM-Array for deep cracks (over 0.1 inches) may provide the capability required for "compliance" monitoring of large cracks to estimate depth on-line. This may be suitable for applications such as monitoring of the tail attach bulkhead on the F-16.

Applications of the MWM and MWM-Arrays with grid methods, in addition to wide area scanning for fatigue damage and on-line crack monitoring, include:

1. Shotpeen quality control using multiple frequency conductivity profiling.
2. Cold work quality control for complex surfaces such as the C-130 propeller fillet region.
3. Residual stress mapping for steel.
4. Coating thickness measurement (e.g. Alclad) and crack characterization under coatings.
5. Deep-penetration MWM-Arrays for hidden corrosion mapping *(under development)*.
6. Object detection, location, and discrimination using large deep-penetration MWM-Arrays (e.g., for landmine detection).
7. Thermal damage monitoring for engine components.
8. Composite degradation and manufacturing quality monitoring (e.g. carbon-carbon composites for aircraft breaking systems).

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